

Humptulips revisited: a revised interpretation of Quaternary vegetation and climate of western Washington, USA

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Abstract

New pollen data from a 770-cm core of a mire at Humptulips on the southwestern Olympic Peninsula (47°17'00"N, 123°54'40"W) and from a nearby deposit regarded as interglacial in age on the West Fork of the Humptulips River provide evidence for a reinterpretation of previous accounts of the Quaternary vegetation and climate. Using a new age model, the highly variable record at Humptulips is here correlated with marine oxygen-isotope stages (OIS) 1–5a. Vegetation during OIS 5a was pine-dominated, mixed woodland and tundra. In OIS 4, 3, and 2, oscillations in pollen assemblages imply repeated intervals of mountain hemlock parkland and tundra. Pine, as an indicator of openness, is also abundant in these stages. Interstadial fluctuations in OIS 3 reflect episodes of lowland western hemlock communities. The earliest of the episodes is of infinite radiocarbon age and the latest dates to approximately 30,000 ¹⁴C yr B.P. Parkland in OIS 2, occurring after 24,600 until at least 18,440 ¹⁴C yr B.P., was replaced by transitional pine–alder in OIS 1 (Holocene), which, unlike any of the earlier stages, conveys the development of modern lowland forest dominated by western hemlock. Pollen assemblages over the length of record imply that temperature and humidity at no time were as high as at present; only in OIS 3 do conditions approach those occurring in OIS 1. During OIS 2, 3, and 4, when tree line apparently stood at the location of the site, climate was colder and drier. Temperatures were depressed an estimated $\geq 5^{\circ}\text{C}$ with precipitation close to 1000 mm compared with 2000–3000 mm at present. Atmospheric circulation during OIS 2 appears to have been much controlled by the location of the Laurentide ice sheet in the continental interior, whereas under the current climatic regime beginning in the early Holocene, westerly air flow has dominated, regulated by interplay between the North Pacific high in summer and the wintertime Aleutian low. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

The lengthy pollen record of a mire at Humptulips is a unique representation of Quaternary vegetation and climate of the North Pacific coast. During initial

reconnaissance of the western Olympic Peninsula (Heusser, 1960, 1964), the antiquity of the pollen record at Humptulips was first realized from assemblages containing quantities of subalpine mountain hemlock. Abundance of mountain hemlock on the lowland, earlier shown by Hansen (1941), indicated an altitudinal depression of some 1500 m and climate similar to conditions near tree line. The Humptulips

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mire proved to date to $>30,000$ ^{14}C yr B.P. and was regarded as covering part of the last glacial cycle (Heusser, 1964).

Subsequent interpretation of Humptulips pollen stratigraphy suggested that the time series began earlier than the last glacial cycle (Heusser and Heusser, 1990). An apparent interglacial pollen assemblage containing western hemlock, older than a date of $63,200$ ^{14}C yr B.P. at a depth of 200 cm in the 770-cm-deep deposit, was correlated with a western hemlock pollen assemblage in marine oxygen-isotope stage (OIS) 5e of core Y72 11 1 from the north-east Pacific Ocean off the Oregon coast (Heusser and Shackleton, 1979). This correlation is now considered doubtful based on our interpretation of new data from Humptulips and from a nearby deposit on the West Fork of the Humptulips River (locations H1 and WF, Fig. 1). The high proportion of western hemlock, among other typically lowland forest components at West Fork, is only matched in the Humptulips record by assemblages of Holocene age. The assemblage formerly correlated with OIS 5e (Heusser and Heusser, 1990) appears better correlated with the base of OIS 3. Consequently, the revised maximum age of the mire is believed to be substage 5a. The significant difference between the two interpretations underscores the difficulty of constructing age models for terrestrial pollen records beyond the range of radiocarbon dating.

Evident in the paleoecological data stemming from the Humptulips mire pollen stratigraphy is the highly variable Quaternary vegetation and climate. At other places on the western Olympic Peninsula foreland, this variability is similarly recorded in related time series that apply to pollen and coleopteran assemblages in sediments exposed in the sea cliff at Kalaloch reaching $>47,000$ ^{14}C yr B.P. (Heusser, 1972; Cong and Ashworth, 1996) and to deposits on both glaciated and unglaciated ground dating to $>48,000$ ^{14}C yr B.P. (Florer, 1972; Heusser, 1974, 1978).

2. Western Washington: Olympic Mountains and adjacent Pacific foreland

The Olympic Mountains (Fig. 1), with summits at >1800 m among the higher peaks, reach maximum

altitude at Mt. Olympus (2428 m). Valleys, deeply cut in the interior of the mountains, open broadly 20 km or more from the ocean between low hills and ridges. The Quinault River, longest of the rivers flowing to the Pacific, runs a southwesterly course some 90 km in length through the study area. Its valley, widening at Quinault Lake, is >20 km across and forms a prominent sector of Pacific foreland.

2.1. Glaciation

During the Pleistocene, the Olympic Mountains developed a central ice and snow complex, drained by peripheral valley glaciers (see general distribution map in Crandell, 1965; also, locations of moraines mapped by Tabor and Cady, 1978). Beyond the western mountain front, the lower Quinault River and contiguous drainage (Fig. 1) cross the greatest expanse of alpine drift on the entire Olympic Peninsula. Morainal loops mark positions of successive piedmont glacial lobes that advanced to within a few kilometers of the ocean. This sector of the peninsula at $47^{\circ}15'–47^{\circ}30'\text{N}$ is the southernmost location of piedmont glaciation directly bordering the Pacific Ocean in western North America.

Moore (1965) mapped the glacial deposits and limits of glaciation in the sector and classified the drift according to a number of criteria including depth of weathering, thickness of weathering rinds on basalt and graywacke clasts, morainal constructional features, and drainage characteristics. Three drift bodies were differentiated (Fig. 1). Donkey Creek till, weathered to a depth of >3.25 m, is localized along the West Fork of the Humptulips River, whereas Humptulips and Chow Chow drifts, each related to distinctive younger episodes of lobe formation, are well distributed across the lower Quinault valley floor.

Outermost Humptulips drift appears as an arcuate apron, weathered to a mean depth of 1.8 m in till and 2.4 m in outwash. Behind a limiting but not well-defined end moraine, Humptulips drift is exposed from north of the Quinault River to the vicinity of the West Fork of the Humptulips River over an arc distance of >20 km; between the Moclips and Copalis Rivers, the deposit, as much as 5 km across, is most extensive along the axis of drainage. The Humptulips mire (H1) and interglacial deposit

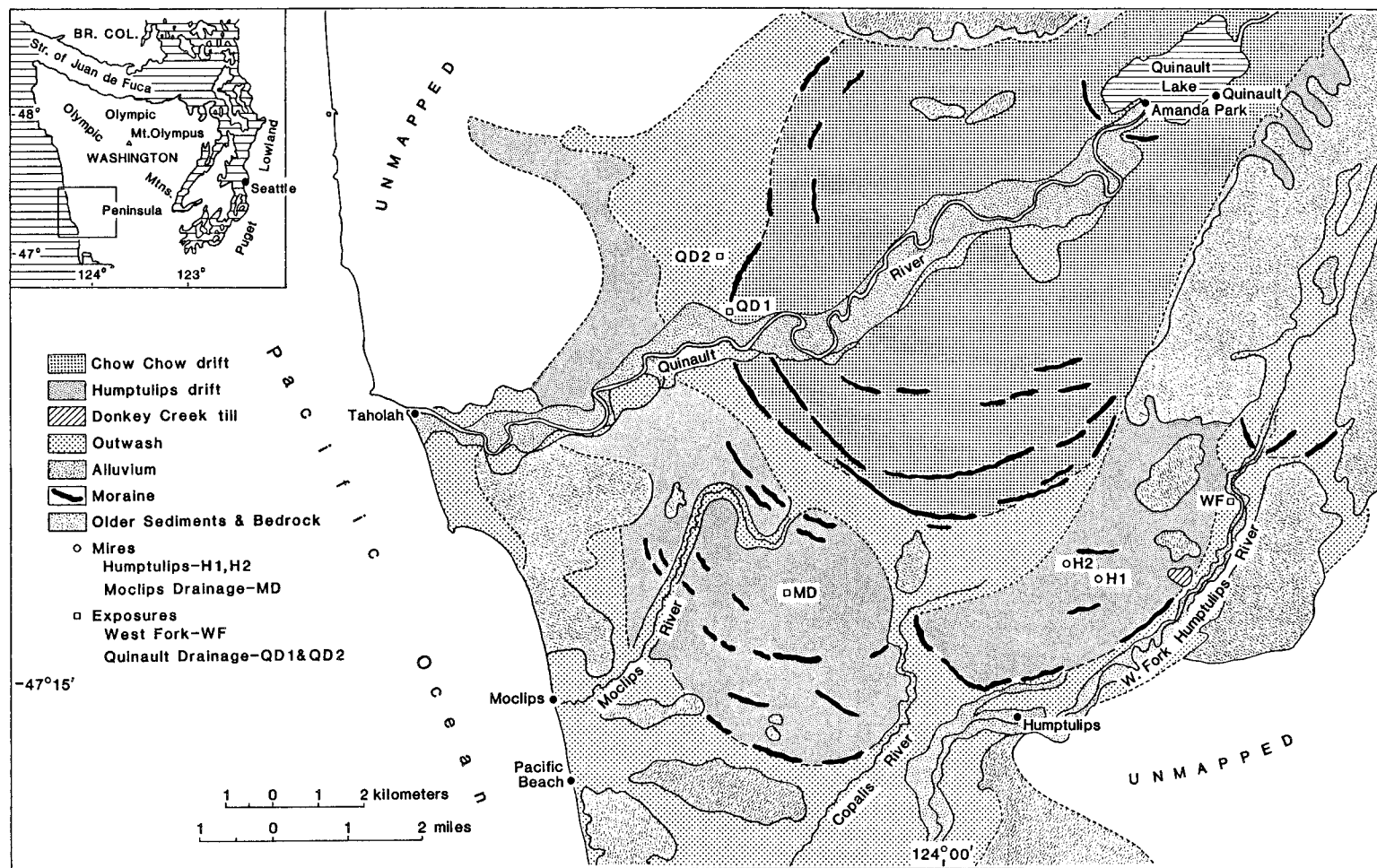


Fig. 1. Surficial geology (redrawn from Moore, 1965) and location of mires and exposures studied in the lower Quinault River sector of the southwestern Olympic Peninsula. Sites reported in this paper are H1 and WF.

on the West Fork (WF) are located in relation to Humptulips drift (Fig. 1).

Chow Chow drift, weathered an average 0.5 m in till and 1.0 m in outwash, flanks the lower course of the Quinault River. Below Quinault Lake, Chow Chow drift has a breadth of about 9 km behind a lengthy, well defined morainal boundary. Several recessional moraines, formed during deposition of the Humptulips and Chow Chow drifts, identify important advances/stillstands of the Quinault glacier. Quinault Lake is held in by the youngest of these moraines.

Ages of the Humptulips and Chow Chow drifts have not been established. Thackray (1996) on the basis of similar weathering profiles tentatively correlated Humptulips drift with drift (Wolf Creek and/or Whale Creek) pre-dating the last interglaciation in the Queets River valley north of the Quinault drainage. North of the Queets, drift in the Hoh River valley (Lyman Rapids, Hoh Oxbow, and Twin Creeks) by the amount of weathering suggested cor-

relation with Chow Chow drift. The Hoh valley drifts were deposited by glacial advances between an estimated 90,000 and 52,000 ^{14}C yr B.P. (Lyman Rapids); between 39,000 and 36,000, 29,200 and 26,700, and 23,000 and 19,500 ^{14}C yr B.P. (Hoh Oxbow); and at $\leq 18,300$ ^{14}C yr B.P. (Twin Creeks).

2.2. Vegetation and climate

Pacific coastal forest clothes the west slope of the Olympic Peninsula (Fig. 2). The forest, under temperate, winter-wet oceanic climate optimum for growth, consists of evergreen coniferous trees of exceptional size and age that range southward along the coast to Oregon and California and northward to British Columbia and Alaska. At the foot of the Olympic Mountains, annual precipitation in the forest averages about 3000 mm and upslope may reach >5000 mm (LaChapelle, 1960; Phillips, 1974). Fog in the valleys at night and in morning hours during July–August significantly reduces evapo-transpira-

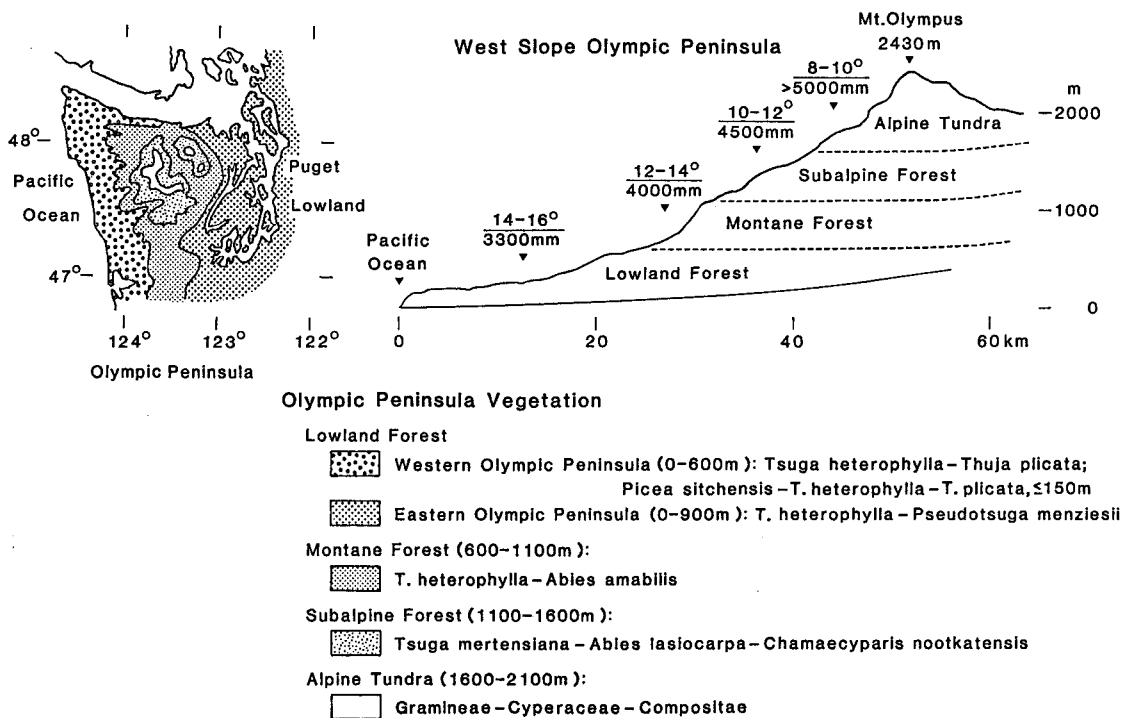


Fig. 2. Vegetation of the Olympic Peninsula and contiguous Puget Lowland (from Franklin and Dyrness, 1973). Vegetation zonation of the west slope of the Olympic Peninsula and mean July temperatures ($^{\circ}\text{C}$) and annual precipitation for each zone are shown schematically (see text for data sources).

tion and helps maintain soil moisture levels during the summer-dry period. Snowfall in the mountains is excessive with snow lines in winter at 450–900 m in altitude; at 2100 m on Mt. Olympus (Fig. 1), snowfall measures >13 m (Phillips, 1974). Average summer temperature, estimated according to a gradient of $0.4^{\circ}\text{C } 100 \text{ m}^{-1}$, ranges from 14° – 16°C across the foreland to 8° – 10°C near tree line (Heusser, 1983). Beginning at sea level, a generalized transect of vegetation on the west slope (Fig. 2) intercepts lowland, montane, and subalpine communities before passing into alpine tundra (Jones, 1936; Franklin and Dyrness, 1973).

Lowland forest of western hemlock (*Tsuga heterophylla*) and western red cedar (*Thuja plicata*) penetrates inland from the ocean at altitudes of ≤ 600 m (Fig. 3). Stands of lodgepole pine (*Pinus contorta*) occur occasionally, scattered among mires and along sluggish drainage courses. At ≤ 150 m, alluvial terraces on broad valley floors feature Sitka spruce (*Picea sitchensis*), bigleaf maple (*Acer macrophyllum*), and black cottonwood (*Populus trichocarpa*)

in advanced stages of succession. Ferns (Filicinae) are common under relatively open canopies, most notably *Polystichum munitum*, *Blechnum spicant*, *Athyrium filix-femina*, *Pteridium aquilinum* var. *pubescens*, and *Polypodium glycyrrhiza*. Beginning with red alder (*Alnus rubra*) along borders of river courses and on frequently flooded adjacent bottomland (Fig. 3), succession terminates on higher terraces in spruce and western hemlock (Fonda, 1974). Sitka spruce in the valleys grows to massive size (Fig. 4).

Forest in the lowland includes mixtures of over-mature Douglas fir (*Pseudotsuga menziesii*) and scattered western yew (*Taxus brevifolia*). Shade intolerant Douglas fir in communities of mature western hemlock, with which it cannot compete, owes its presence to openings in the forest canopy attributed to windfall, fire, and other causes. Once established, the species may endure for centuries, its thick bark resistant to fire. On drier leeward slopes of the Olympic Peninsula, where competitive pressure from western hemlock is less, Douglas fir predominates.



Fig. 3. Lowland forest with communities of alder, cottonwood, and Sitka spruce on terraces along the Quinault River above Quinault Lake.



Fig. 4. Typical old-growth Sitka spruce in valley bottom along the Queets River.

Western hemlock and Pacific silver fir (*Abies amabilis*) dominate montane forest between altitudes of 600 and 1100 m (Fonda and Bliss, 1969). Both are highly shade-tolerant, competitive species. A winter snowpack, lasting in the forest until late spring/early summer, acts to condense atmospheric water vapor and maintain high humidity and soil moisture. After the snowpack melts, seed germination and development of seedlings and saplings are limited to a short growing season. Pacific silver fir apparently is better adapted than western hemlock to survive burial beneath a long-lasting snowpack, which may account for its local abundance in montane communities.

Subalpine forest, the uppermost band of tree growth at 1100–1600 m (Fonda and Bliss, 1969), is distinguished by stands of mountain hemlock (*Tsuga mertensiana*), subalpine fir (*Abies lasiocarpa*), and Alaska yellow cedar (*Chamaecyparis nootkatensis*). Closed forest extends to about 1500 m in altitude and, thereafter, stands become relatively open, fragmented into patches and files occupying parkland (Fig. 5). Wet meadows, fed by melting snow and containing a variety of herbs, are part of the ecotone

at tree line. Conditions similar to those imposed on reproduction by a persistent snowpack in montane forest also apply to the subalpine forest. Climatic trends since the Little Ice Age, however, resulting in glacier recession and reduction of year-long snow cover (LaChapelle, 1960), have allowed tree seedlings to invade formerly snow-blanketed parkland (Fig. 6).

Alpine tundra at higher altitudes beyond the ecotone is distributed in the interior of the Olympic Mountains, limited in extent by bedrock, avenues of mass wastage, ice, and snow. Tundra occurs most prominently on the higher peaks and surrounding ramparts of the Mt. Olympus summit complex. Above mixed forest–tundra at 1500–1600 m, alpine plants grow at altitudes as high as 2100 m in places protected from wind, flowering during the short growing season that climaxes in June–July. Plants belonging to the Gramineae, Cyperaceae, and Compositae (Tubuliflorae and Liguliflorae) are common, among less prominent families that include Liliaceae, Caryophyllaceae, Ranunculaceae, Cruciferae, Saxifragaceae, Rosaceae, and Scrophulariaceae.



Fig. 5. Open mountain hemlock and subalpine fir forest above the fog-covered Hoh River valley.



Fig. 6. Parkland of subalpine forest and tundra. Distant skyline is the western shoulder of Mt. Olympus.

3. Modern pollen fallout as an index of vegetation

The relationship between surface pollen and source vegetation is of significance in the interpretation of vegetation and climate from fossil pollen assemblages. Nevertheless, surveys conducted on the Olympic Peninsula (Heusser, 1969; Florer, 1972) reveal only a general affinity between pollen spectra and forest communities and tundra. Data are skewed toward low-altitude sites, where the greater proportion of sampling was done; in addition, the proximity of vegetation zones over restricted altitudinal distances results in much dispersion of extra-local pollen, such that data often are not site specific. Pollen of alder and western hemlock produced on the Olympic

foreland, for example, is wind-transported in quantities inland to montane, subalpine, and alpine zones. Alder, the primary component, is a superior pollen producer. While abundant in the lowland after logging, alder is throughout strongly overrepresented.

A greater parallel between pollen spectra and community components comes from a latitudinal survey (Fig. 7) containing a larger spread of surface pollen sites along the North Pacific coast (Heusser, 1985). Vegetation following a climatic gradient changes gradually between the forest of Washington and Alaskan tundra, unlike vegetation subject to close-order altitudinal zonation in the Olympic Mountains, and pollen spectra become more site representative. In Washington, sites principally with

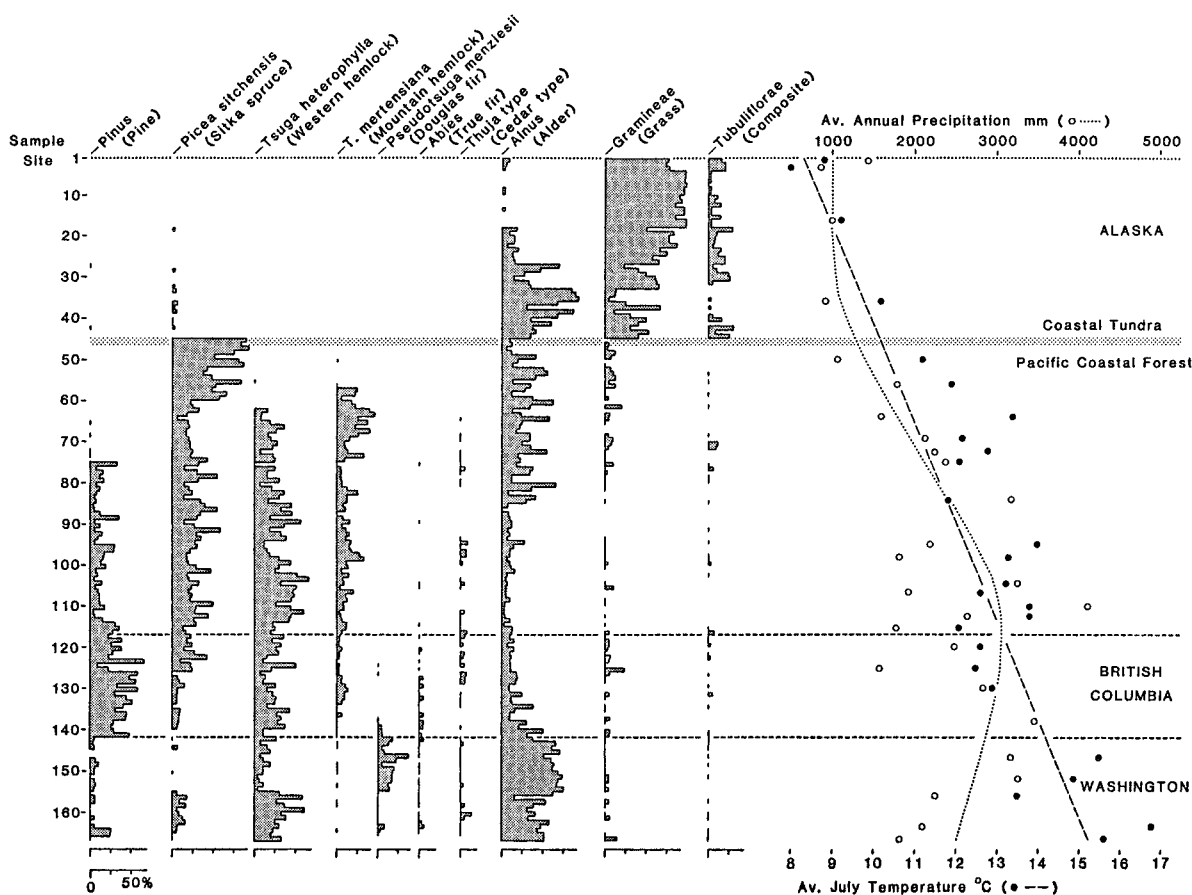


Fig. 7. Frequency (%) of important taxa in surface pollen samples of North Pacific coastal forest and tundra at stations ranging between Washington and the western Aleutian Islands in Alaska (redrawn from Heusser, 1985). Pollen data are plotted in conjunction with average July temperature and annual precipitation as a basis for interpreting paleoclimate from fossil pollen frequencies.

western hemlock, spruce, and alder (155–162) reflect the source of pollen in lowland forest on the western Olympic Peninsula; sites containing conspicuous quantities of alder and Douglas fir (142–154) equally portray forest in the Puget Lowland.

British Columbia sites (117–141) mirror western hemlock–spruce–cedar forest and imply, by way of a decrease in alder in the region sampled, comparatively less disturbance than in Washington. Many of the sampling sites are mires, a habitat for lodgepole pine (*Pinus contorta*), which produces abundant pollen and is therefore overrepresented in the spectra. Mountain hemlock, first recorded at sea level in the northern part of coastal British Columbia, proportionately increases northward to Alaska.

Pollen of forest sites in Alaska (45–116) derives chiefly from dominant western hemlock. Within the range of western hemlock (site 62), sites trace the shift to dominance by mountain hemlock. Beyond the range of mountain hemlock (site 57), the forest composition shifts to Sitka spruce, the solitary component of forest at the coastal tundra boundary (site 45). Pine, its source mostly in small stands in mire communities, is overrepresented in Alaska as in British Columbia. Successional communities following glacier recession in the coastal mountains apparently are responsible for the high percentages of alder (*Alnus rubra* and/or *A. sinuata*) seen in the Alaskan record.

The contact between forest and tundra, recognized in pollen spectra by the sharp decrease of Sitka spruce, is matched by an increase of alder pollen with that of grass and composite. Alder (sites 37–44) in notable amounts results from its immediate presence in a forest–tundra ecotone. Sites in tundra (1–36), beyond the range of alder, appropriately show an abundance of grass with composite.

Pollen fallout in Pacific coastal forest/tundra (Fig. 7) covers a mean July temperature gradient that decreases at sea level from between 14° and 15°C in Washington to 10° and 11°C at the forest limit in Alaska; temperatures at coastal tundra sites beyond the tree line are as low as 8°C. Values correspond remarkably well with the temperature range for the west slope of the Olympic Mountains (Fig. 2). In contrast with the average annual precipitation in the forest (2000–3000 mm), precipitation in the tundra is less than 1000 mm.

4. Materials and methods

A 770-cm-long core (H1C) of interbedded peat, organic silt, silt, and clay overlying gravel was taken at Humptulips with a Hiller sampler and sampled at 5-cm intervals. Samples were also collected at 2-cm intervals from the wall of a pit (H1P) dug 220-cm deep at a point ~10 m from the core location. Bulk samples from the pit served to produce high-resolution records of pollen and spores, macrofossils, and loss-on-ignition measurements. At the West Fork of the Humptulips River (WF), twenty-six samples were taken from a unit of peaty/woody silt and sand interbedded with gravel exposed stratigraphically over a vertical distance of ~8 m.

Samples were prepared in the laboratory (processing, LEH) following the procedure of Heusser and Stock (1984), which employs nylon microscreens to concentrate the 10–150- μ m-size pollen/spore fraction. Pollen and spores in each sample were identified and counted under the microscope using modern reference material (analyses, CJH). Frequencies (%) of upland tree and shrub/herb pollen derive from identifications of $n \geq 300$ and pollen of aquatics/cryptogam spores from $n \geq 300$ pollen and spores; unidentified pollen/spores amount to $\leq 2\%$. Frequency data are shown stratigraphically in diagrams, zoned according to peak frequencies of key taxa. Species epithets are given where identification is assured; in other cases, identity is to genus, family, or higher rank. Haploxylon/Diploxylon species of pine (*Pinus contorta/monticola*) and lowland/montane species of alder (*Alnus rubra/sinuata*) are undifferentiated. In the case of spruce (*Picea sitchensis*), the record may include *P. engelmannii*, which although rare on the Olympic Peninsula at present (Hitchcock et al., 1969), was possibly more numerous in the Pleistocene. Designated as types are *Thuja* type, representing inaperturate *Thuja plicata*, *Chamaecyparis nootkatensis*, and *Taxus brevifolia*, and *Polygonum bistortoides* type, which includes *P. viviparum*. Compositae include *Artemisia* and other unidentifiable Tubuliflorae, as well as Liguliflorae. Plant nomenclature follows Hitchcock and Cronquist (1973).

Macrofossils also identified through use of a reference collection were counted under the microscope from stratigraphic samples taken from the wall of

Table 1

Radiocarbon dates, Humptulips core (H1C) and pit (H1P), and West Fork of the Humptulips River (WF)

Site	Depth (cm)	Material dated	Age ^{14}C yr B.P.	Laboratory Number
H1C	35	Sphagnum peat	2410 \pm 120	Y-2530
H1C	45	Sphagnum peat	3870 \pm 160	Y-2531
H1C	80	Detritus peat	8550 \pm 250	RL-229
H1C	90	Silt	10,475 \pm 240	GX-3544
H1C	110	Silt	18,440 \pm 100	QL-1458
H1C	125	Organic silt	24,600 \pm 600	Y-2441
H1C	140	Organic silt	26,000 \pm 150	GL-1459
H1C	160	Organic silt	33,400 \pm 200	QL-1463
H1C	170	Silt	33,800 \pm 1400	Y-2442
H1C	200	Silt	>47,000	Y-2443
H1P	200	Wood	63,200 \pm 1400	QL-1464
WF	560	Wood	>61,000	QL-17

the pit and core at H1 (processing and analyses, DMP). Samples subjected to macrofossil analysis were soaked overnight in 5% KOH solution and washed with water through screens with meshes of 1.0, 0.5, and 0.25 mm. Screened material included seeds, fruits, leaves, stems, macrospores, and charcoal.

Loss-on-ignition (%) measurements supplement pollen/spore and macrofossil data from the H1 pit. Samples were first oven-dried at 105°C for 48 h and later combusted in a muffle furnace for 1 h at 550°C.

The age model for the Humptulips core (H1C) was constructed by interpolation and extrapolation of ten radiocarbon dates (Table 1) and by placement of B.P. OIS 4/5a boundary (73,000 yr; Martinson et al., 1987) at 710-cm core depth. Dates (uncorrected) from bulk samples were virtually all reported by the Yale Geochronometric (Y) and Quaternary Isotope Laboratories (QL). Organic sediments dated in the core are from 5-cm core lengths, each centered at pollen-stratigraphic levels; wood samples served to date the base of the pit (H1P) and the exposure on the West Fork of the Humptulips River (WF).

5. Quaternary records: location, stratigraphy, and chronology

5.1. Humptulips (H1; 47°17'00"N, 123°54'40"W)

Site H1, 7 km northeast of the town of Humptulips, is a topogenous mire set in a closed basin at

100 m in altitude on drift, <2 km inside the limit of the Humptulips lobe (Fig. 1). Its surface estimated at <1 ha in area at the border of disturbed low-land forest is covered by sphagnum moss (*Sphagnum papillosum* Linb.), bog laurel (*Kalmia occidentalis*), Labrador tea (*Ledum groenlandicum*), and burnet (*Sanguisorba officinalis*).

5.1.1. Core pollen and spore record (H1C)

Sixteen pollen assemblage zones (Fig. 8) are recognized, chronologically controlled by radiocarbon dates that reach >47,000 ^{14}C yr B.P. at 200 cm depth in Zone H1C-7.

Zone H1C-16 (710–770 cm; *Pinus*–*Salix*–*Alnus*–Gramineae–*Artemisia*–*Isoetes*). *Pinus* is dominant with Gramineae and *Artemisia*, implying open communities of mixed pine woodland and tundra, in which, late in the interval, *Salix* and *Alnus* increase. Shade intolerant *Pinus*, abundant throughout most of the Humptulips record, was apparently favored by openness of the terrain, generally windy conditions, and continuing omnipresence of a seed bed consisting of highly mineralized glacial deposits.

In lower Zone H1C-16, limited amounts of *Picea*, *Tsuga heterophylla*, and *T. mertensiana* suggest for a time the presence of small local stands of these trees together with *Alnus* in a cool temperate climate. Alternatively, however, these taxa may represent reworked material, occurring as they do in association with gravel and gray clay at the base of the core. *T. heterophylla* in the early part of the Humptulips record is subject to long-term suppres-

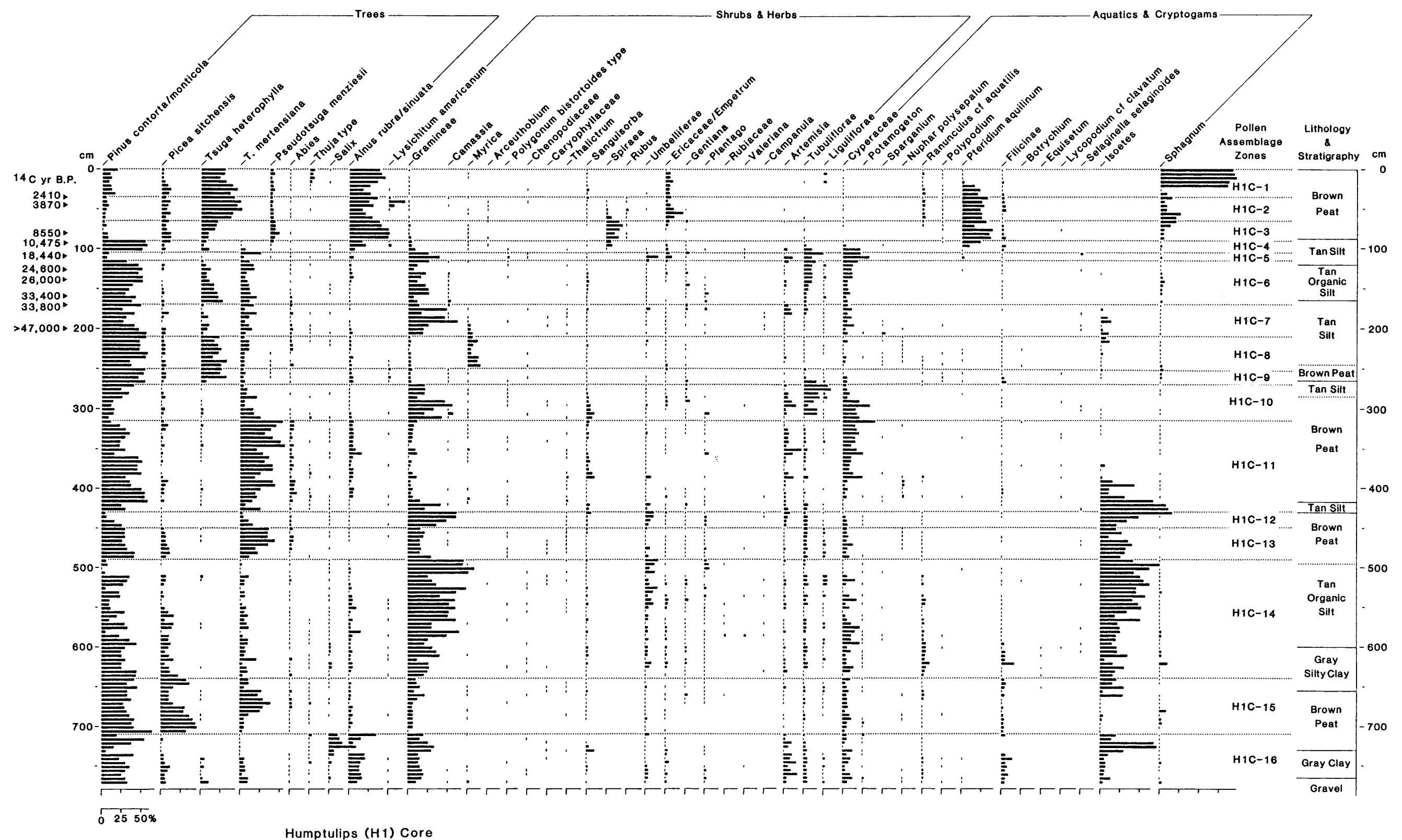


Fig. 8. Pollen and spore frequency (%), lithology, and radiocarbon dates for the core (H1C) taken in the 770-cm-deep Humptulips mire. Sampling interval is 5 cm.

sion and does not expand significantly until much later (Zone H1C-9). *Alnus* also is not abundant again until even later (Zones H1C-3 through H1C-1). *Salix* and *Alnus* in Zone H1C-16 represent an early stage of plant invasion on glacial drift following collapse of the Humpulips lobe.

The sequence of gravel overlain by clay and, in turn, by peat bracketed by zone H1C-16 covers an initial lacustrine paleoenvironment in which the aquatic *Isoetes*, following Cyperaceae, rises to peak proportions.

Zone H1C-15 (640–710 cm; *Pinus–Picea–Tsuga mertensiana*–Gramineae). The apparent trend toward arboreal dominance initiated in upper Zone H1C-16 continues through Zone H1C-15, giving rise to high frequencies of *Pinus*, *T. mertensiana*, and *Picea*. The large proportion of *Pinus* (40–63%) may reflect its presence at the site, possibly on peat substrates formed after early lacustrine sedimentation (note the interruption in the *Isoetes* profile). Gramineae and other open-grown taxa are much less frequent than in Zone H1C-16.

Zone H1C-14 (490–640 cm; Gramineae–Umbelliferae–*Pinus–Picea–Tsuga mertensiana–Isoetes*). Reduction and ultimate elimination of arboreal species is accompanied by a maximum of Gramineae (83%). Reflecting a setting at or near tree line, the maximum is the highest of all the assemblage zones. Coincident with the Gramineae, the equally impressive increase of *Isoetes* in the silty clay and organic silt points toward renewed and steadily maintained lacustrine conditions.

Zone H1C-13 (450–490 cm; *Tsuga mertensiana–Pinus–Picea–Gramineae*). The assemblage is reminiscent of Zone H1C-15 by its peak amount of *T. mertensiana*. Frequencies of *Picea*, nonetheless, are much lower and Gramineae somewhat higher than in Zone H1C-15. The assemblage may be considered a variant, one of several indicative of shifting climate at the edge of open subalpine forest during intervals of peat formation (note also Zone H1C-11 higher in the core). While favoring *Pinus* at these times, hydrological changes apparently caused a reduction or absence of *Isoetes*.

Zone H1C-12 (435–450 cm; Gramineae–Umbelliferae). Assemblages in this zone and in the upper part of Zone H1C-14 are much alike. The increase in frequency of Gramineae to 61–62%, although

substantial, is less than the amount (83%) reached earlier. The implication from the minimal arboreal component of both H1C-14 and H1C-12 is of near-treeless vegetation under cold conditions.

Zone H1C-11 (315–435 cm; *Tsuga mertensiana–Pinus–Abies–Isoetes–Cyperaceae*). Amounts of *T. mertensiana* in Zone H1C-11 are at core maxima (53–56%). The increase of *T. mertensiana* in the zone, simultaneous with a reduction of *Pinus*, is suggestive of progressive consolidation of forest stands over time. The continuing presence of *Abies* is suggestive of *A. lasiocarpa*, an associate of *T. mertensiana* in the sub-alpine zone of the Olympic Mountains today.

Exceptional quantities of *Isoetes* (86–90%), highest in the entire core at the base of Zone H1C-11, coincide with an interval of silt deposition/ponding prior to the accumulation of overlying sedge (Cyperaceae) peat.

Zone H1C-10 (270–315 cm; Gramineae–Tubuliflorae–*Pinus*). Zone H1C-10 shows high frequencies of Gramineae and repetition of the expansion of tundra, as inferred previously for Zones H1C-14 and H1C-12. Within Zone H1C-10, the shift from Gramineae to Tubuliflorae–*Pinus* dominance parallels a lithological change from peat to silt. The trend terminates with successive appearance of *Tsuga heterophylla* in Zone H1C-9, representing what appears to be a directional change regulated by increasing warmth favoring transitional Tubuliflorae.

Zone H1C-9 (250–270 cm; *Pinus–Tsuga heterophylla–Pseudotsuga–Lysichitum*). The assemblage warrants attention because it reveals a sharp restructuring of arboreal vegetation during a milder, more humid interval following the colder and drier interval of Gramineae-dominated tundra (Zone H1C-10). Frequencies of *T. heterophylla* as high as 32% are the highest recorded thus far in the record. Placed against a backdrop of *Pinus* (52%), frequencies approach amounts found in lowland forest communities (see Fig. 7). Of additional significance in Zone H1C-9 is the earliest presence of *Pseudotsuga menziesii*, an associate of *T. heterophylla* in present-day lowland forest.

Zone H1C-8 (210–250 cm; *Pinus–Tsuga heterophylla–Pseudotsuga–Myrica*). Zone H1C-8, by its distinctiveness of *Myrica* and loss of *Lysichitum*, represents a modification of the Zone H1C-9 assemblage. The presence of *Myrica* in the lower part of a

thick silt unit and of *Isoetes* in the upper part (Zones H1C-8 and H1C-7) implies a developing lacustrine setting. *M. gale* is the species well established today in the lowland, growing along impeded drainage courses and in swamps (Jones, 1936).

Zone H1C-7 (170–210 cm; Gramineae–*Pinus*–*Tsuga mertensiana*). Zone H1C-7 is the first of two zones characterized by increased frequencies of Gramineae. Indicative of parkland and a return to colder climate, the assemblage interrupts the continuity of *T. heterophylla* between Zones H1C-8 and H1C-6. The base of the zone is dated $>47,000$ ^{14}C yr B.P. and the top is dated $33,800 \pm 1400$ ^{14}C yr B.P.

Zone H1C-6 (115–170 cm; *Pinus*–*Tsuga heterophylla*–*T. mertensiana*–Gramineae–Tubuliflorae). Peak frequency of *T. heterophylla* (27%) dates to about $33,400 \pm 200$ ^{14}C yr B.P., above which frequencies progressively decrease and become minimal by $26,000 \pm 150$ and after $24,600 \pm 600$ ^{14}C yr B.P. Apparent at first is a sharp change to milder, more humid climate, which is characteristic of Zones H1C-9 and H1C-8; later, increasingly colder, drier climate forcing greater openness in the vegetation evidently contributed to the decline of *T. heterophylla*, the rise of *Pinus* and Tubuliflorae, and variable frequencies of *T. mertensiana* and Gramineae.

Zone H1C-5 (105–115 cm; Gramineae–Umbelliferae–Tubuliflorae–Cyperaceae–*Tsuga mertensiana*). The assemblage contains peak frequencies of Gramineae and other subalpine parkland taxa, which reflect mostly tundra under a cold, relatively dry climate much in the same manner as in Zones H1C-14, H1C-12, H1C-10, and H1C-7. The time frame for the zone is imprecise but is younger than 24,600 and extends to after $18,440 \pm 100$ ^{14}C yr B.P.

Zone H1C-4 (90–105 cm; *Pinus*–*Alnus*). *Pinus* and *Alnus* (16–20%) constitute an initial stage in the transition of vegetation from tundra to forest. Stands first dominated by *Pinus* and later by *Alnus* preceded the development of lowland forest. *Pinus* frequencies (54–57%) compare with peak amounts reached earlier in much of the core record. The age of upper Zone H1C-4, $10,475 \pm 240$ ^{14}C yr B.P., dates a similar *Pinus*–*Alnus* assemblage at site QD2 in the Quinault drainage (Fig. 1; Heusser, 1983).

Zone H1C-3 (65–90 cm; *Alnus*–*Pseudotsuga*–*Tsuga heterophylla*–*Spiraea*–*Pteridium*). Zone H1C-

3 features shade intolerant *Alnus* at maximum frequency (48–50%) dated approximately 8550 ± 250 ^{14}C yr B.P. Much in the same manner that *A. rubra* grows today, *Alnus* became important in early successional stages in the Holocene. Stands containing *T. heterophylla* and *Pseudotsuga menziesii*, open at first and providing sufficient light for *Pseudotsuga* to reproduce, were established on better-drained soils. Bracken fern (*Pteridium aquilinum* var. *pubescens*) and spiraea (*Spiraea douglasii*), similarly light-demanding as *Alnus*, characterize understories beneath open tree canopies.

Zone H1C-2 (35–65 cm; *Tsuga heterophylla*–*Alnus*–*Lysichitum*–Ericaceae/*Empetrum*–*Pteridium*–*Sphagnum*). Peak frequencies of *T. heterophylla* (49–51%) following a decline in *Alnus* imply much expansion of closed lowland forest in a late stage of succession. Nevertheless, substantial amounts of *Alnus* (15–32%) and *Pteridium* (24–27%) indicate some community openness. Replacing *Spiraea*, Ericaceae/*Empetrum* heath with *Sphagnum*, and for a time *Lysichitum*, provide a record of sequential hydrological change. Dates bracketing an apparent interval of humification, identified by peak *Lysichitum*, are 3870 ± 160 and 2410 ± 120 ^{14}C yr B.P.

Zone H1C-1 (0–35 cm; *Tsuga heterophylla*–*Thuja* type–*Pinus*–*Alnus*–*Sphagnum*). Zone H1C-1 traces the last approximately 2400 ^{14}C years of record, during which *T. heterophylla* (26%) fell below its standing in Zone H1C-2 at the expense of increasing *Alnus* (45%). Virtual elimination of *Pteridium* carries the implication that communities of *T. heterophylla* with the addition of *Thuja* type (*Thuja plicata*/*Taxus brevifolia*) were mostly closed.

Peat deposition under wet, temperate climate, continuing to the present day, was enhanced by proliferation of *Sphagnum*. *Pinus*, as a non-competitive species, is often associated with open *Sphagnum* mires, which may explain its increased frequency in the assemblage as the mire expanded.

5.1.2. Pit pollen and spore record (H1P)

The pit provides detail of the stratigraphy of the uppermost portion of the mire deposit (Fig. 9). Its pollen and spore record (Fig. 10), as might be expected, is basically not unlike the core record (Fig. 8) where the two overlap. Thus, Zones H1P-1 through H1P-6 appear to correlate with Zones H1C-1 through

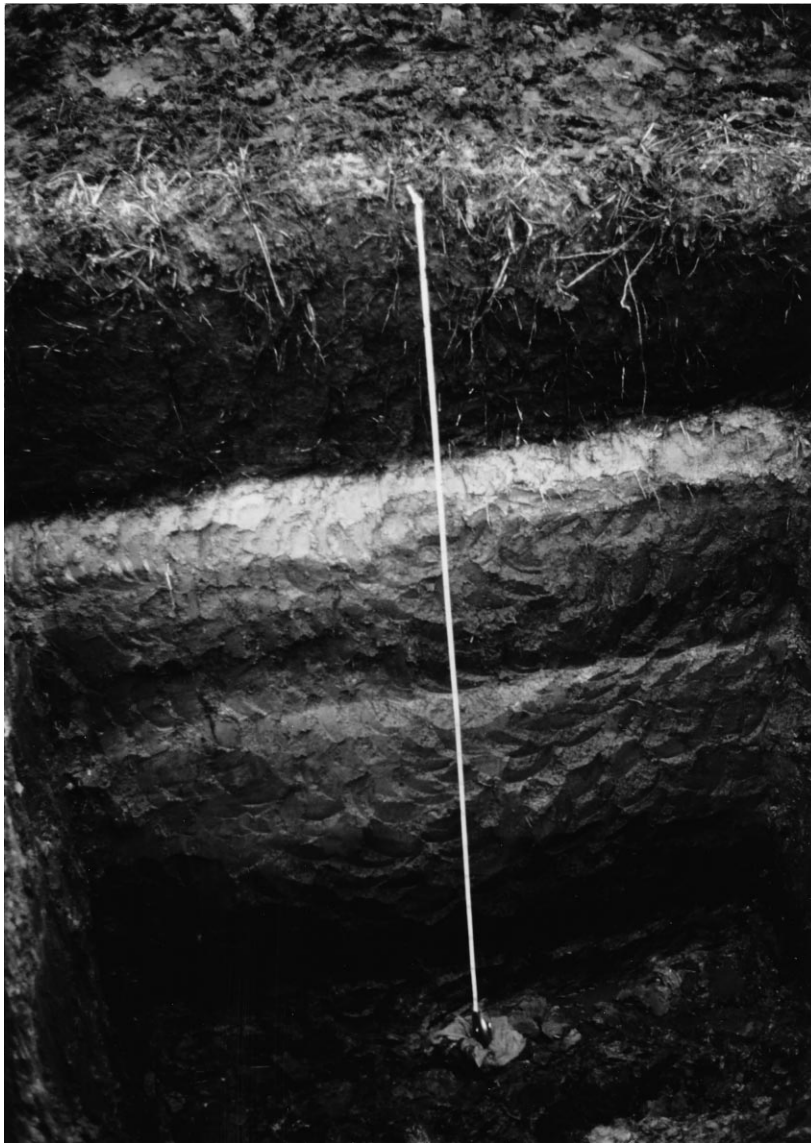


Fig. 9. Depositional sequence exposed in pit (H1P) dug 220-cm deep at Humptulips. Peat (65-cm thick) overlies leached white silt (20-cm thick) with successive underlying beds of silt, organic silt, and peat.

H1C-6, while below, Zones H1P-7 through H1P-11 are correlated with Zones H1C-7 through H1C-9. However, certain differences apparent in the records indicate the extent to which assemblages at sampling points in proximity to each other may vary. Notice, for example, compared with Zone H1C-5 (Fig. 8), the considerable frequency of *Pinus* and small amount of Gramineae in Zone H1P-5 (Fig. 10); also, the absence of *Spiraea* in Zone H1P-3 ver-

sus Zone H1C-3. Close-interval sampling of the pit stratigraphy singled out two additional assemblage zones: H1P-10 (*Pinus*–*Tsuga heterophylla*–*Lysichitum*) and H1P-8 (*Pinus*–*Tsuga mertensiana*–Gramineae–Tubuliflorae) shown in Fig. 10. Both represent gradational episodes between zones recognized in the core sequence.

Lithostratigraphic units and their thicknesses in the pit and core are variable, apparently the result of

contrasting sedimentary processes at each point on the mire. Thicknesses also may vary as a result of the effect of seasonal drying and flooding on contraction or expansion of the depositional body at the different times when the core was taken and the pit dug. Apparent in the pit sequence are units of white (7.5YR 8/0) and dark gray (10YR 4/1) silt, among layers of tan organic silt (7.5 YR 4/2). Directly underlying the acidic, *Sphagnum*-rich brown peat (10YR 2/2–7.5YR 4/6), the white silt uppermost is striking, apparently having been subject to leaching (Fig. 9).

Trends in the loss-on-ignition profile (Fig. 10), delineating changes in organic content of the deposit, tend to follow the pattern expressed by *Tsuga heterophylla*. Higher percentages in each of these parameters are mutually associated in Zones H1P-1, H1P-2, H1P-6, and H1P-9 through H1P-11. Milder climate implied by *T. heterophylla* at these times appears also to have effected greater organic productivity.

5.1.3. Macrofossil records

Macrofossils from the lower part of the core (H1C, 280–770 cm, Fig. 11) versus the pit (H1P, 0–220 cm, Fig. 12) are fewer both in number and recognizable taxa. The small size of samples (1–2 cm³) taken from the core is undoubtedly a factor contributing to the difference. Numbers of macrospores/seeds of aquatics (*Isoetes*, *Potamogeton*, *Nuphar*) show adherence to their corresponding spore/pollen frequencies (Fig. 8); particularly coincidental are peak values of *Isoetes* (Zones H1C-11, H1C-12) and *Nuphar* (Zone H1C-11). Numbers of *Selaginella selaginoides*, cf. *Ericaceae*, and *Gramineae* are not clearly allied in the respective records; *Juncus* frequently encountered as a macrofossil is not recorded by its pollen. Among arboreal species, *Picea sitchensis* leaves, sterigmas, and seeds establish an early presence corresponding at depth to increased pollen frequencies (Zones H1C-16–H1C-13). While *Tsuga heterophylla* is rare at depth (only leaves recorded at three levels) and matches its low pollen incidence, macrofossils of *T. mertensiana* are unrecorded, contrasting high frequencies at different times in the pollen record.

Of macrofossils identified and counted in samples from the pit, few were numerous. Of these,

macrospores of *Isoetes*, in part identified as *I. cf. echinospora*, reveal a much greater presence (Zones H1P-9–H1P-8) than their microspore counterpart (Fig. 10). This is also the case with macrospores of *Selaginella selaginoides*, which proved to be more abundant and have wider stratigraphic range (Zones H1P-11–H1P-3) than microspores (Zones H1P-9–H1P-4). Seeds of *Juncus*, as in the core, occur sporadically in numbers through Zone H1P-2. In Zone H1P-1, profiles of macrofossils and pollen/spores of the Cyperaceae, *Kalmia/Ledum* (*Ericaceae*), and *Sphagnum* are not unlike each other. Charcoal (unmeasured) distributed at most levels at and above Zone H1P-11 reveals a lengthy history of fire.

5.2. West Fork of the Humptulips River (WF; 47°17'06"N, 123°50'15"W)

The West Fork at a point 5.5 km northeast of the Humptulips mire is actively cutting the side of the valley along the course of a sharp meander (Fig. 1). In the upper part of a measured section, interbedded glaciofluvial gravel, sand, and silt, above an altitude of 75 m at river level, total about 18 m in thickness. At the top, 1–1.5 m of eolian silt (loess) is overlain by modern forest soil. Below the glaciofluvial unit in the lower section is an ~8-m-thick complex of peaty/woody silt, sand, and gravel beds regarded as interglacial in age. The complex (Fig. 13), in turn, rests on 1.5 m of fine-textured, laminated sediments, which are obscured at and beneath river level. Plant remains among the woody debris include stems, roots, and numerous pistillate cones of *Tsuga heterophylla*. Logs in the exposure are compressed and measure 30 cm across; others downstream, eroded from the exposure, were found to be as much as 40 × 60 × 200 cm. Wood from a depth of 580 cm in the exposure of organic debris (Zone WF-3) is dated >61,000 ¹⁴C yr B.P.

Ponding of the drainage as a proglacial lake is implied by the estimated several hundred laminae exposed in the basal sediments. Gravel resting disconformably above the laminated sediments is considered to be outwash deposited after the barrier holding the lake was breached. Overlying deposits are almost entirely the result of fluvial aggradation, the beds of peaty/woody silt/sand constituting overbank or terrace deposits, apparently formed mostly

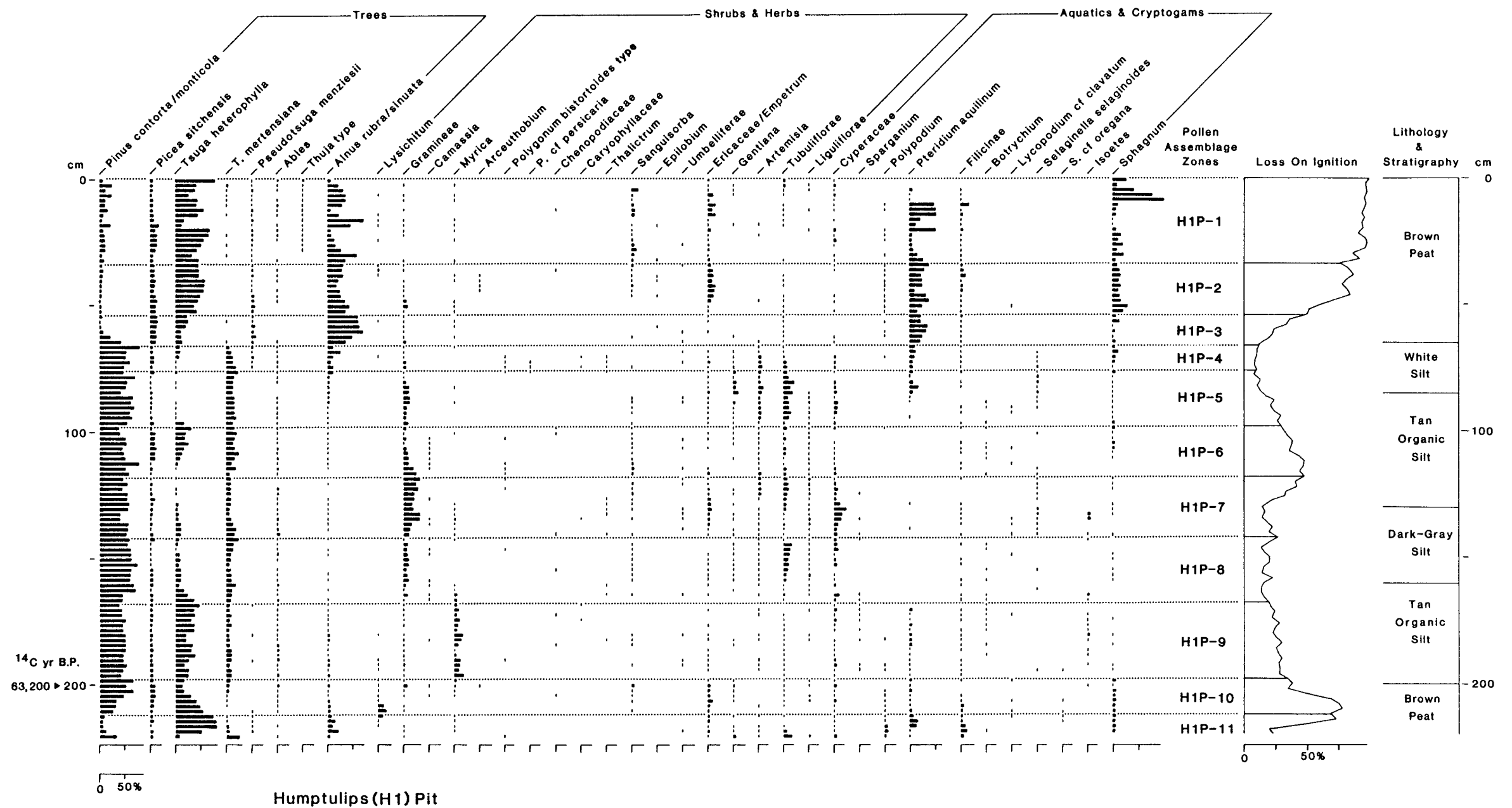


Fig. 10. Pollen and spore frequency (%), lithology, loss on ignition, and radiocarbon date at depth of samples taken from the wall of pit (H1P) at Humptulips. Sampling interval is 2 cm. Note change in frequency scale when comparison is made with the core (H1C) pollen and spore record (Fig. 8).

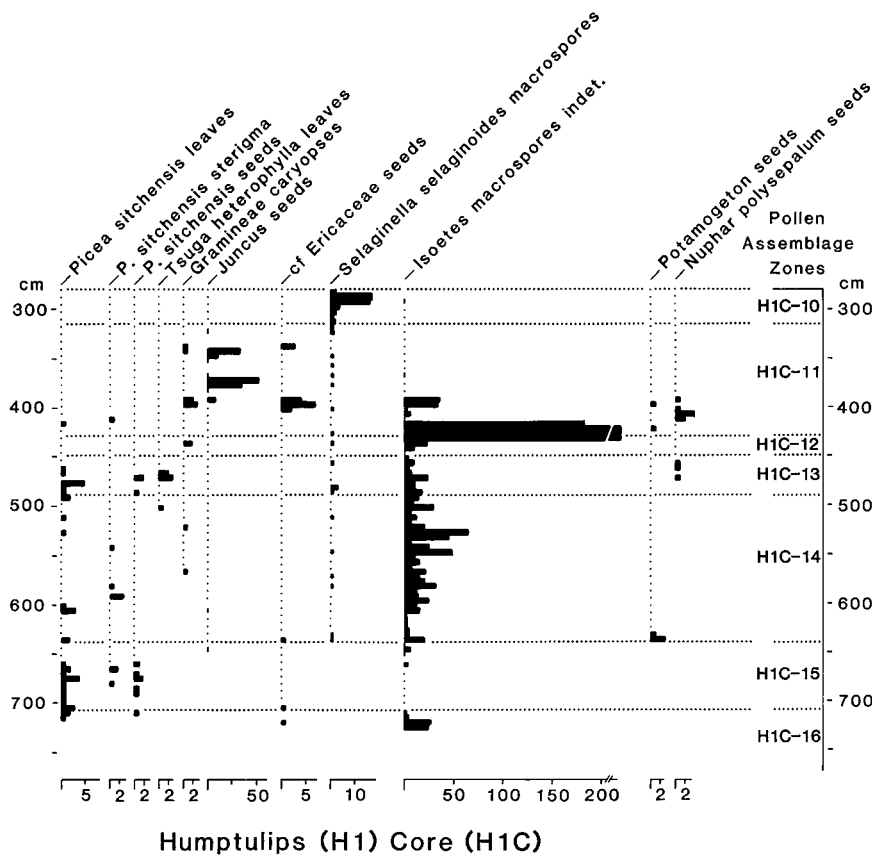


Fig. 11. Macrofossil diagram of lower part (280–770 cm) of Humptulips core (H1C) sampled at 5-cm intervals. Numbers indicated are per 1–2 cm³ of sediment. Pollen assemblage zones correspond to zones shown in Fig. 8. Note variable scales.

under a low-energy regime in backwaters of the drainage. The uppermost 18 m dominated by gravel are mapped as Humptulips drift (Moore, 1965).

Justification for assigning an interglacial age to the peaty/woody unit is found in the pollen assemblages of the West Fork exposure (Fig. 14), which essentially characterize forest similar to the modern lowland forest of *Tsuga heterophylla* and *Picea sitchensis* containing *Alnus*. Significant among the assemblages are minor quantities of lowland species, *Pseudotsuga menziesii*, *Lysichitum americanum*, *Pteridium aquilinum* var. *pubescens*, and *Selaginella* cf. *oregana*. Fluvial transport of pollen/spores from vegetation at higher elevations of the drainage, for example, *Tsuga mertensiana*, *Polygonum bistortoides* type, and *Lycopodium selago*, may account for some presence of a subalpine component among the pollen spectra. The organic beds at West Fork are assigned to the last in-

terglaciation, but they could be older. However, the absence of similar beds in the overlying Humptulips drift implies uninterrupted glacial discharge since the last interglaciation.

Six pollen assemblage zones (Fig. 14) characterize the vegetation and environmental conditions at the time of deposition of the peaty/woody unit. Lithological changes inherent in the measured section, especially with the repeated emplacement of gravel, are a reflection of the shifting pattern of drainage and the cause for discontinuity in the pollen/spore stratigraphy.

Zone WF-6 (samples 21–26; *Picea*–*Tsuga heterophylla*–*Alnus*–*Filicinae*). The assemblage with equal amounts (>25%) of *Picea* and *T. heterophylla* suggests an early stage of river terrace plant succession (Fonda, 1974). At this time, prior to deposition of the extensive Humptulips drift sheet, the river flowed in

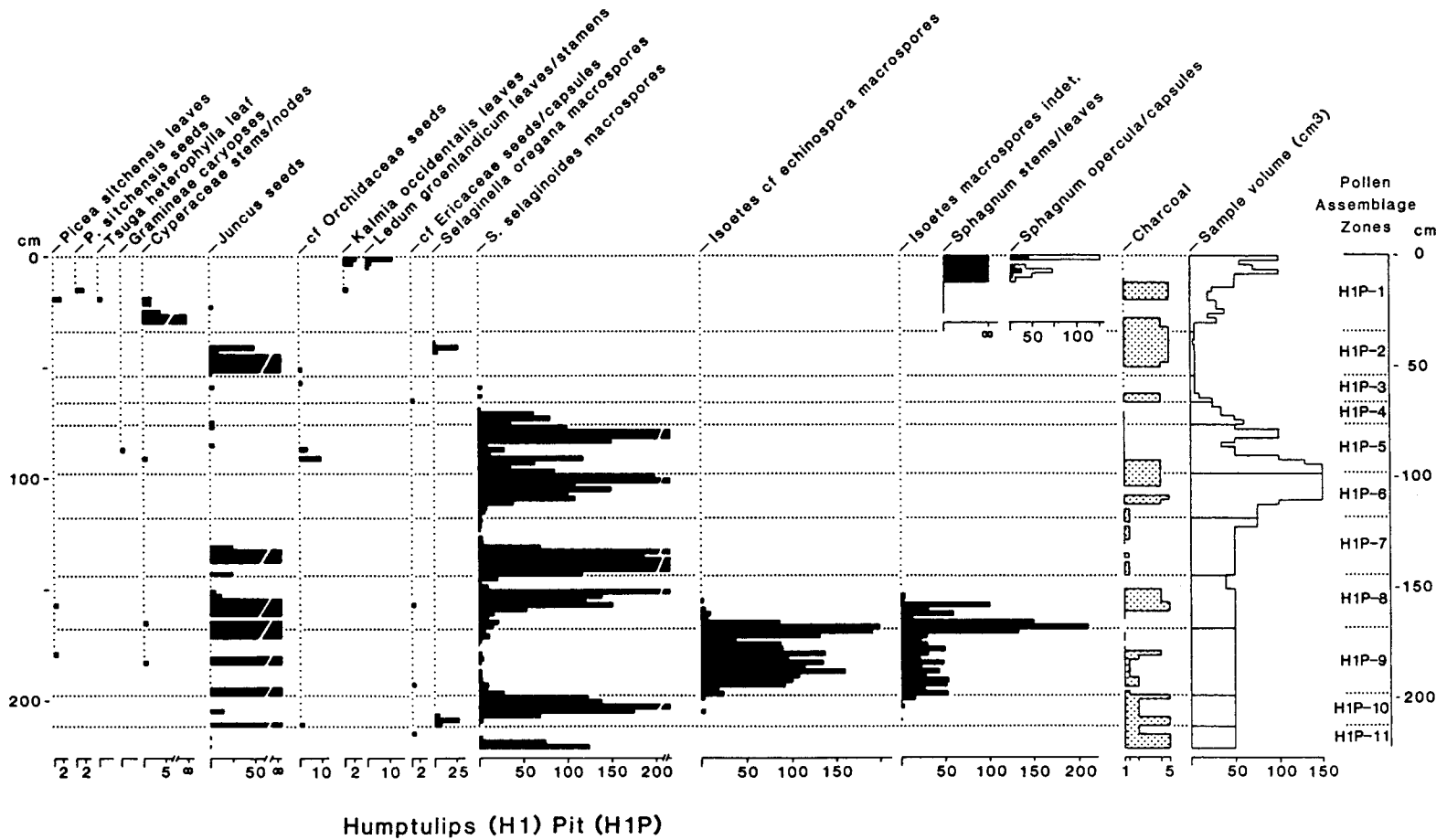


Fig. 12. Macrofossil diagram of samples taken every 2 cm (0–220 cm) from wall of pit (H1P) at Humptulips. Numbers are mostly per ≥ 50 cm³ of sediment; amounts of charcoal follow a relative abundance scale of 1–5. Pollen assemblage zones correspond to zones in Fig. 10. Note variable scales.



Fig. 13. Slumped block of peaty/woody silt/sand and underlying gravel at WF on the West Fork of the Humptulips River. Block is shown resting on laminated silt exposed in place at and above river level.

a broad, less topographically confined valley. *Alnus* reaching >25% is typical of open stands containing high frequency Filicinae (>50%).

Zone WF-5 (samples 12–20; *Tsuga heterophylla*–*Picea*–Filicinae). Zone WF-5 represents a late stage in terrace succession, identified by developing preponderance of *T. heterophylla* (64%). Trends show much reduction of *Picea* (15%) and replacement of *Alnus* by *T. heterophylla*.

Zone WF-4 (samples 8–11; *Tsuga heterophylla*–*Picea*–*Pinus*–Filicinae). Variability observed in Zone WF-4, the result of a shift in the successional trend, apparently stems from community disturbance caused by repeated deposition of stream gravel.

Zone WF-3 (samples 5–7; *Tsuga heterophylla*–*T. mertensiana*–*Pinus*–Filicinae). Frequencies of *T. mertensiana* (15–29%) are greater than seem likely to be caused by fluvial transport of pollen from the subalpine zone. These amounts may cover an episode of cooler climate that interrupted the continuity of an otherwise milder interglaciation. Similar frequencies occur in surface samples in forest containing *T.*

mertensiana to the north in coastal British Columbia and Alaska, where climate is cooler than in lowland forest of western Washington (see Fig. 7).

Zone WF-2 (samples 3–4; *Tsuga heterophylla*–Filicinae). At 68–70% in Zone WF-2, *T. heterophylla* achieves its highest frequency. The maximum presumably coincides with the establishment of closed lowland forest under a milder climate following the cooler conditions implied in Zone WF-3.

Zone WF-1 (samples 1–2; *Pinus*–*Picea*–*Tsuga heterophylla*–*Alnus*–Cyperaceae). Decrease in frequency of *T. heterophylla* to 22%, subsequent to the deposition of 240 cm of gravel, suggests a return to forest containing *Picea* and disturbance-adapted *Pinus* and *Alnus*. The assemblage appears coincident with the shift toward greater deposition of coarse-grained sediments in a high-energy fluvial environment. Silty peat covered by Zone WF-1 is the uppermost of organic beds in the West Fork exposure, above which are massive deposits of glaciofluvial gravel and sand.

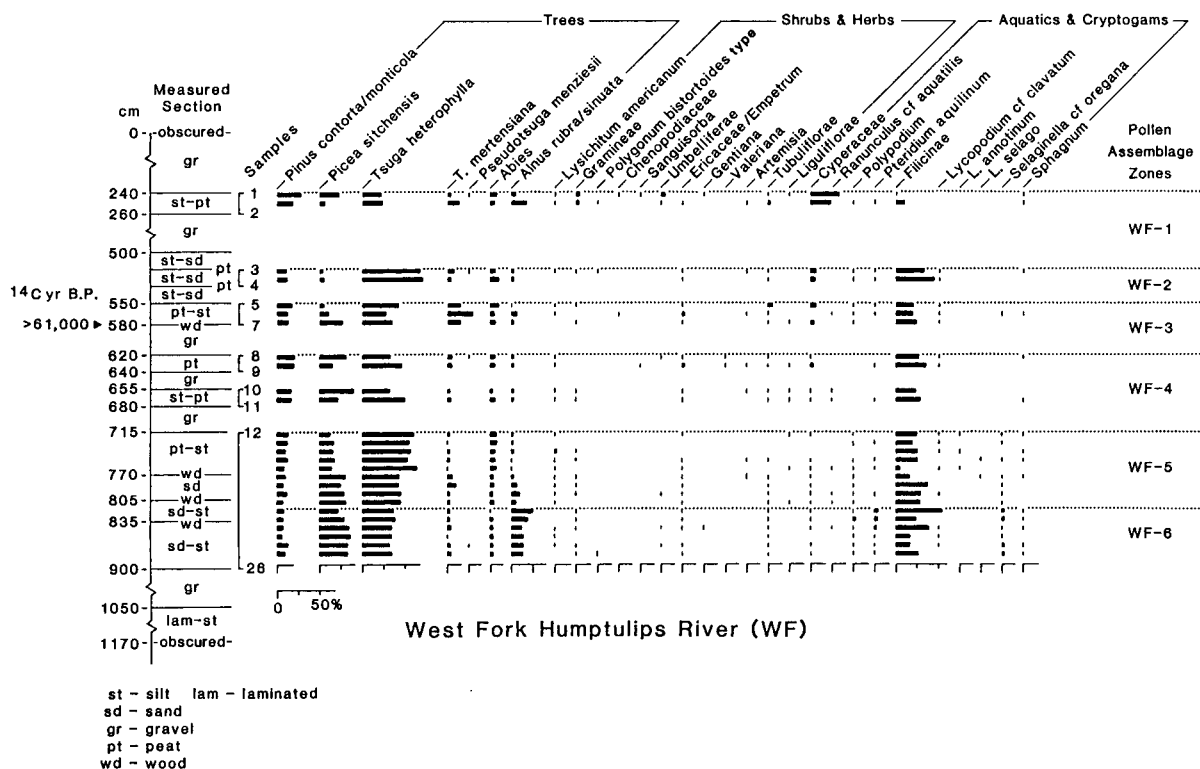


Fig. 14. Pollen and spore diagram of peaty/woody silt/sand unit, pollen zones, and radiocarbon date of samples collected in measured section exposed at WF on the West Fork of the Humptulips River (Fig. 13).

6. Discussion and conclusions

It is apparent that downcore in the mire pollen stratigraphy, no assemblages are found to clearly match assemblages in the present interglaciation (Holocene) at the top of the core. Interglacial assemblages (Zones H1C-1–H1C-3) in the Humptulips core (Fig. 8) and at the West Fork (Fig. 14) are well represented by characteristic *Tsuga heterophylla*, *Alnus*, and Filicinae (including *Pteridium*) of lowland forest provenance; *Pinus*, by comparison, is not well represented. In contrast, Zones H1C-8 and H1C-9, which exhibit *T. heterophylla* in some abundance, albeit much less than in Zones H1C-1–H1C-3, show minimal amounts of *Alnus* and Filicinae and predominance of *Pinus*. Frequencies in Zones H1C-8 and H1C-9 resemble amounts registered in correlative Zone ISL-5 in a previously studied core of Humptulips mire (Heusser, 1964). The record from the Humptulips pit (H1P) shown in Fig. 10, es-

pecially wherein frequencies of *T. heterophylla* are high and those of *Pinus* low (Zone H1P-11), offers greater similarity with the present interglaciation. Nevertheless, amounts of *Alnus* and Filicinae remain low. Thus, the presence of an interglaciation held earlier for Zones H1C-8 and H1C-9 (Fig. 8) and consolidated in Zone 8 by Heusser and Heusser (1990) appears indefensible on palynological grounds.

We propose that this revised age model places Humptulips drift which underlies the Humptulips mire in OIS 5b. Although Thackray (1996), using weathering criteria, correlated Humptulips drift with pre-last interglaciation Wolf Creek and/or Whale Creek drift, our preference is for correlation with younger Lyman Rapids drift, which he dates earliest at 90,000 yr B.P. (OIS 5b) and as late as 52,000 ¹⁴C yr B.P. (OIS 3). Correlation of older Wolf Creek and/or Whale Creek and Humptulips glaciations would require evidence of one or more interglaciations in the Humptulips core (H1C).

Assemblages that may correlate with the West Fork interglacial record in western Washington occur in a sea cliff exposure (47°38'20"N, 124°23'00"W) at Kalaloch (Heusser, 1972). Its glacial geological setting reinterpreted by Thackray (1996) suggests that deposition of sediments, originally estimated at 70,000 yr B.P., began in OIS 5. If this is the case, the assemblage in Zone I-2 (fig. 3 in Heusser, 1972) containing high frequency *Tsuga heterophylla*, *Alnus*, and Filicinae (recorded as Polypodiaceae) and low *Pinus* is most indicative of interglaciation. Transfer function equations applied to the assemblage show July temperatures close to the modern mean of 14.5°C (Heusser et al., 1980). At another allegedly interglacial site located in South Aberdeen (46°57'15"N, 123°48'30"W) dated at >53,000 ¹⁴C yr B.P. (K.L. Pierce, pers. commun., 1979), the equations gave average July temperature as high as 14°C, when similarly applied to pollen spectra dominated by *T. heterophylla* and Filicinae with low levels of *Pinus* (L.E. Heusser, unpubl. data).

Interglacial temperatures in Washington, much like the present but also lower than today by 1–2°C, show geographic variation. This amount of temperature variability applies equally to the present interglaciation, where conditions were sequentially cooler before and after times of maxima. In the case of the interglacial Whidbey Formation in the Puget Lowland east of the Olympic Peninsula (Fig. 1), extremes of temperature appear to have been greater, owing perhaps to the increased continentality of the location (Heusser and Heusser, 1981). Farther east in the Cascade Range, with greater openness in the interglacial vegetation compared to the present, climate during the last interglaciation appears to have been warmer and drier than in the Holocene (Whitlock and Bartlein, 1997).

Pollen diagrams of the Humptulips core (Fig. 15) juxtapose pine, Sitka spruce, western hemlock–cedar type, mountain hemlock–true fir, alder–Douglas fir, and grass–composite, under the assumption that, following withdrawal of the Humptulips lobe, fluctuations of these ecologically significant components of western Washington vegetation represent primarily much the same response to climatic forcing as at present. Correlation beyond the limit of radiocarbon dating is based on a parallel implied between changing climate in the Humptulips record and stages of

global ice volumes. Pollen assemblages/zones and their equivalent marine oxygen-isotope stages are estimated as follows: H1C-16, OIS 5a; H1C-10–H1C-15, OIS 4; H1C-7–H1C-9, OIS 3; H1C-4–H1C-6, OIS 2; and H1C-1–H1C-3, OIS 1. Ages of stage boundaries are according to Martinson et al. (1987).

Assemblages of pine and grass–composite covering OIS 5a infer predominance of pine woodland and tundra. Pine pollen in abundance signifies disturbance and a general condition of community openness that continued through OIS 2. Well adapted to open windswept landscapes containing nutrient-poor soils, pine invaded and flourished on moraines and outwash laid bare in the wake of glacial retreat. The climate was apparently cooler, windier, and generally less mesic than it was at the beginning of OIS 5a, when under conditions that apparently initially were more interstadial in character, spruce and western hemlock were present in numbers. The frequent siltiness of beds shown by the closed-basin lithostratigraphy (Figs. 8 and 10) attests to a significant amount of eolian transport of silt from surrounding terrain.

Mountain hemlock–true fir and grass–composite pollen assemblages coupled with decline of Sitka spruce in OIS 4 registers a cooling trend consistent with development of subalpine parkland–tundra. Successive maxima in the pollen frequencies of the principals indicate a measure of variability in temperature and humidity levels in OIS 4. That the Chow Chow lobe became activated is most likely under the cold climate at this time. Multiple moraines in the lower Quinault drainage (Fig. 1) offer evidence of this activity. While the final advance of the Chow Chow lobe appears to have taken place later, climatic conditions during OIS 4 imply a phase of substantial lobe enlargement.

Early OIS 3 from its display of a western hemlock–cedar type assemblage follows under milder, more humid interstadial climate. Later, rising pollen frequencies of mountain hemlock–fir record an interval of colder climate, which culminated with grass–composite peak frequencies. The Chow Chow lobe probably reached its outer position during OIS 3. Glacier recession afterward was apparently a late OIS 3 event marked by a short interstade represented by increased quantities of western hemlock–cedar type pollen centered at about 30,000 yr B.P.

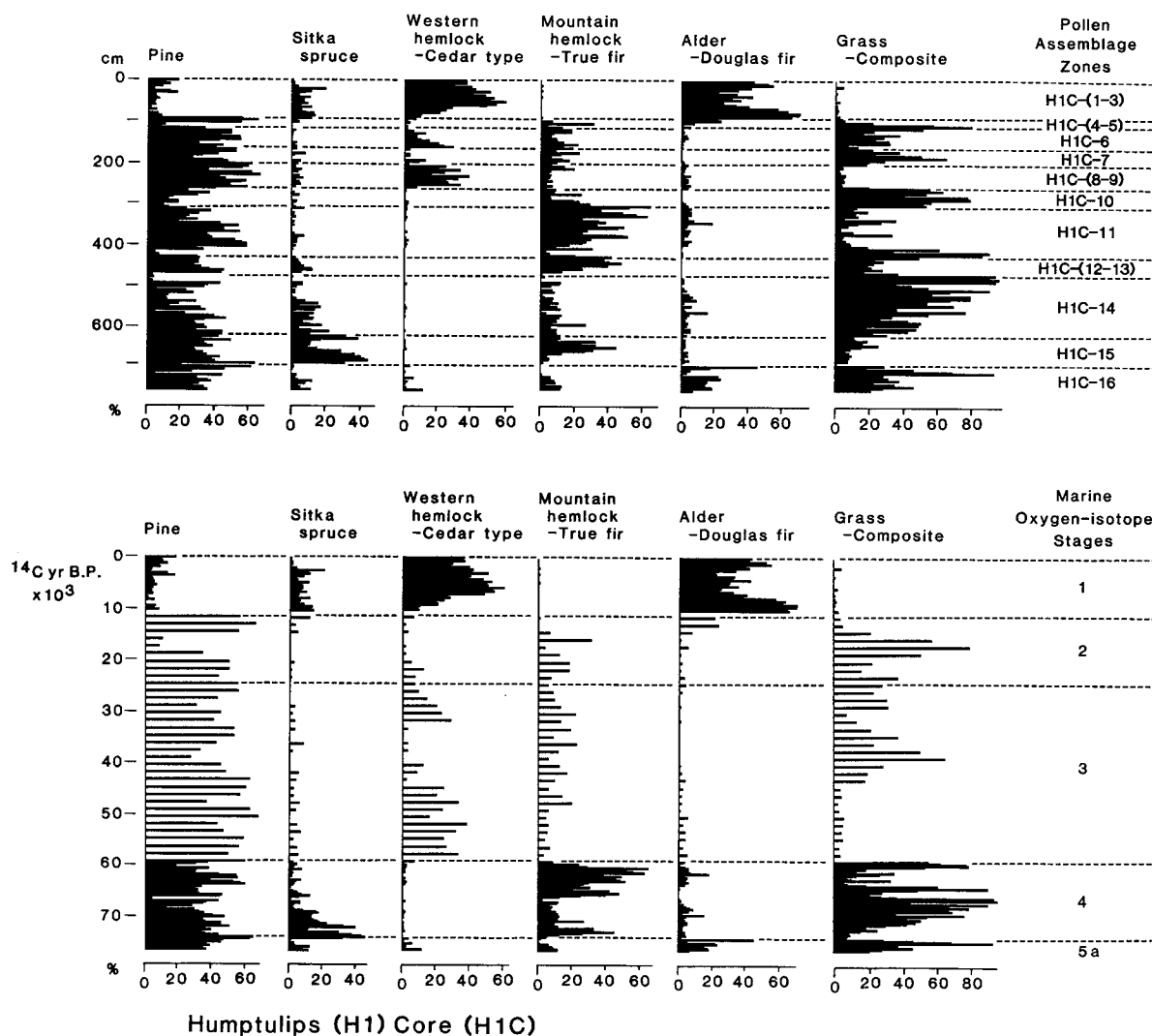


Fig. 15. Pollen frequency (%) diagrams of ecologically significant taxa in the Humptulips core (H1C) drawn (above) to a depth scale with zonation as in Fig. 8, and (below) plotted with age.

OIS 2 shows high-frequency grass-composite pollen in association with mountain hemlock-true fir, which conveys the ultimate interval of parkland associated with cold, drier, and windy stadial climate. Peak development of the grass-composite assemblage occurred after 24,600 until at least 18,440 ^{14}C yr B.P. (Fig. 8). As a response to cold climate at this time, the prominent moraine fronting Quinalt Lake upvalley, by its size and position, is presumed to be a OIS 2 construction. It may correspond to moraine formation of Hoh Oxbow age, which Thackray (1996)

places between approximately 23,000 and 19,500 ^{14}C yr B.P. There is no basis to infer a younger age, possibly related to a Younger Dryas event, as implied by data collected elsewhere along the North Pacific coast (Engstrom et al., 1990; Mathewes et al., 1993; Peteet and Mann, 1994; Lund and Mix, 1998; Pike et al., 1998). No evidence in support of such an assignment is apparent in either the core (H1C) or pit (H1P) pollen stratigraphy (Figs. 8 and 10).

A silt layer in OIS 2, clearly defined beneath the top peat layer in Fig. 9, is part of a blanket of loess

widely distributed on the western Olympic Peninsula. Its maximum age is dated to 15,180 ^{14}C yr B.P. (Thackray, 1996). Thicknesses of >1 m for the loess occur in exposures along the West Fork of the Humptulips River and at the tops of sea cliffs between the mouths of the Quinault and Hoh Rivers (Florer, 1972; Heusser, 1972); in the drainage of the lower Quilayute River, north of the Hoh, the loess, typically columnar in structure, is 4-m thick. The silt is associated with extreme windiness, especially evident at Humptulips by the presence of reworked extinct Pliocene diatoms. The diatoms are attributed to eolian transport from geological formations in south-central Oregon and southwestern Idaho (J.P. Bradbury, pers. commun., 1982). They were carried along a north-west vector by wind circulating around the high-pressure cell over the Laurentide ice sheet. Their occurrence is extensive, similar diatoms having been found at Battle Ground Lake in southwestern Washington (Barnosky, 1985) and in a marine core off southern Oregon (Sancetta et al., 1992). The circulation pattern effecting redeposition of the Pliocene diatoms, outlined by Barnosky et al. (1987), suggests that much pine, characteristic of the drier interior of Oregon, also was wind-transported, contributing to its considerable frequency during late OIS 2 and possibly earlier stages downcore at Humptulips.

In OIS 1, abundant pollen of pioneering alder–Douglas fir followed by western hemlock–cedar type have no precedent in the record. With dwindling of North American ice sheets, as climate warmed, winds that during OIS 2 were predominantly from the interior became oceanic. Akin to the modern style of circulation, North Pacific high pressure with high levels of insolation prevailed at first along the coast during summer (Heusser et al., 1985). Increase of temperature and moderate levels of humidity initially supported the advance of alder–Douglas fir. Subsequently, the Aleutian low became increasingly entrenched in the system between September and May, resulting in wet winters, shorter, cooler summers, and greater humidity in support of the more mesic western hemlock-dominated forest.

Communities of pine and later of alder–Douglas fir leading up to the development of lowland western hemlock–cedar forest constitute a successional sequence observed not alone at Humptulips but also in other parts of the Olympic Peninsula (Peterson

et al., 1983; McLachlan and Brubaker, 1995). A regional portrait of the principal components is likewise well developed in marine sediments off Oregon (Sancetta et al., 1992). Extending back 30,000 ^{14}C years to OIS 3, pollen in the marine core exhibits trends comparable to those on the Olympic Peninsula and remarkably similar to trends in a core from the Oregon Coast Range (Worona and Whitlock, 1995).

OIS 1 warmer climate invoked much reshuffling of cold-adapted species whose pollen was in evidence in OIS 2 and earlier. Migratory movement in the Olympic Mountains was considerable, as species adjusted their ranges at higher altitudes and latitudes. Plants vacating the lowland and relocating at or near tree line include *Tsuga mertensiana*, *Polygonum bistortoides*, *Gentiana* (cf. *G. calycosa*), *Valeriana* (cf. *V. sitchensis*), *Campanula* (cf. *C. piperi*–*C. rotundifolia*), and *Artemisia* (cf. *A. trifurcata*–*A. norvegica*–*A. campestris*). The arctic–alpine, circumpolar *Selaginella selaginoides*, abundant in OIS 2–4 but no longer extant in the Olympics, migrated to higher latitudes of the North Pacific during and following late Quaternary deglaciation (Heusser and Igarashi, 1994).

Underscoring a lengthy record of climatic variability, the time series at Humptulips (Fig. 15) makes plain the rapid and repeated buildup, breakdown, and replacement of communities in the Quaternary vegetation of western Washington. The implication of the reconstructed vegetation is of temperature and humidity at no time as high as in OIS 1. When tree line fell close to the vicinity of Humptulips during OIS 2, 3, and 4, colder and drier climate was in effect. Temperature depression amounted to an estimated $\geq 5^{\circ}\text{C}$ with precipitation totaling close to 1000 mm by comparison to 2000–3000 mm at present. Atmospheric circulation during stage 2 apparently was controlled by the Laurentide ice sheet in the continental interior, whereas under the modern climatic regime, westerly air flow dominates the region, regulated by interplay of the North Pacific high in summer and the wintertime Aleutian low. Modern Pacific coastal forest generated during recent millennia, by its structure and species complexity, has gained a level of advancement unequalled for >100,000 years. In view of past evidence, the forest, however unique at present, seems destined to eventual replacement through forcing by future climatic regimes.

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